CURING OF HIGH-PERFORMANCE CONCRETE FOR STRENGTH: WHAT IS SUFFICIENT?

by

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Synopsis: This paper reports the results of an exploratory study on the effects of curing duration on the variation of mortar strength with distance from the drying surface. A novel, notched cylindrical test specimen was adopted for measuring tensile strength at different depths. Two mortar mixtures with *w/c* of 0.30 and 0.45 were used; the former was assumed to be representative of the paste system in a high-performance concrete. Specimens were moist cured for (1, 3, or 7) d and then exposed to air at 25 °C and 50 % or 70 % RH. The cylinders were sealed to simulate one-dimensional drying in a large member. Tensile strengths were measured at 28 d. Relationships between tensile strength and depth were compared with those of specimens continuously moist cured. The data tended to show that 1 d of moist curing might be sufficient to ensure adequate strength development at a depth of 25 mm from the exposed surface. The phenomenon of increasing strength with drying may have confounded the results, and recommendations for additional studies are provided.

Keywords: curing; drying; high-performance concrete; mortar; tensile strength

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BACKGROUND

Motivation for Study

In 1990, the National Institute of Standards and Technology (NIST) organized an international workshop to:

- Identify ongoing and planned research programs on high-performance concrete;
- Identify potential applications where high-performance concrete could be used on a routine basis;
- Identify technical barriers to widespread use of high-performance concrete;
- Identify institutional barriers and deficiencies in standards which hinder the use of high-performance concrete;
- Develop a listing of critical research to overcome the technical barriers and provide a sound basis for the needed standards.

The workshop, co-sponsored by the American Concrete Institute, was attended by prominent international experts in various aspects of concrete technology. The workshop proceedings (Carino and Clifton 1990) adopted the following definition of high-performance concrete:

Concrete having desired properties and uniformity which cannot be obtained routinely using only conventional constituents and normal mixing, placing, and curing practice. As examples, these properties may include:

- *Ease of placement and compaction without segregation*
- *Enhanced long-term mechanical properties*
- *High early-age strength*
- *High toughness*
- *Volume stability*
- *Long life in severe environments*

The above definition was modified and adopted in 1998 as the ACI definition of high-performance concrete, as follows (Russell 1999):

> *Concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices.*

Examples of desired characteristics were included in a "commentary" to the ACI-definition. The above definitions have been criticized as being too broad and not practical for specification purposes. Consequently, others (Zia et al. 1991; Goodspeed et al. 1996) have defined different classes of high-performance concrete with specific properties. In general, the majority of high-performance concretes used in North America can be characterized as concretes with water-cementitious materials ratios (*w/cm*) lower than about 0.4. The term "water-cementitious materials ratio" is used instead of "water-cement ratio" because other cementitious materials (pozzolans or ground slag) besides portland cement are typically used to produce high-performance concrete. Thus high-performance concrete typically has high compressive strength and high resistance to fluid penetration.

The proceedings of the NIST/ACI workshop provided an outline of primary and secondary research needs within the following general areas:

- Materials and proportioning
- Processing and curing
- Mechanical properties and test methods
- Durability and test methods
- Structural performance and design
- Standards and acceptance criteria

The outline of research needs has provided a roadmap for a multi-faceted, long-term research program on high-performance concrete at the National Institute of Standards and Technology. The following research needs related specifically to curing were identified (Carino and Clifton 1990):

- Evaluate the effectiveness of moist curing considering the completeness of hydration as a function of time;
- Seek an understanding of interactions between ambient exposure conditions, mixture rheology, and needed evaporation control measures;
- Develop a more comprehensive understanding of the effects of internal curing temperature, and develop guidelines for curing high-performance concrete based on sound technical knowledge.

One of the first curing-related studies in the NIST program established the applicability of the maturity method to high-performance concrete (Carino et al. 1992). The study that is reported in this paper represents the initial experimental effort to establish the basis for the duration of the moist curing period for high-performance concrete. Prior to initiating the experimental program, the authors prepared a report on the state-of-the-art related to curing of high-performance concrete (Meeks and Carino 1999). That report covered the following topics:

- Review of the characteristics of high-performance concrete;

- Review of the physical and chemical properties of cement paste related to curing;
- Historical review of the ACI building code requirements for curing;
- Review of other curing recommendations, standards, and criteria;
- Review of recent research on curing requirements;
- Recommended research needs.

Curing Requirements in the ACI Building Code

A review of the predecessors to ACI 318-95 revealed that the general requirements for curing of concrete have changed very little since the first standard regulations were proposed in 1909 (Meeks and Carino 1999). The basic requirement has been to cure concrete made with normal portland cement for a period of at least 7 d and to cure high-early-strength concrete for at least 3 d.

Tests reported by Price (1951) indicated that normal strength concrete that is moist cured for 7 d and then stored in air will attain approximately the same 28-day strength as if it had been continuously moist cured. These tests provide validation of the 7-day criterion in the ACI Code. Since high-early-strength concrete will gain strength more rapidly, the Code permits a 3-day curing period.

In the 1971 Code, a requirement was added to maintain the concrete temperature above 10 °C during the curing period. This addition is to ensure that sufficient strength development will occur during the prescribed minimum curing periods. In addition, a new provision was added for checking the adequacy of curing procedures based on strength tests of field-cured cylinders. Both requirements were carried over to the 1995 version of ACI 318.

The ACI Code, however, makes no distinction between strength and durability considerations with regard to curing requirements. Since ACI 318 deals primarily with structural safety, the provisions are intended primarily to ensure adequate structural capacity. The only explicit mention of durability in relation to curing is contained in the provisions (originally added in 1971) dealing with accelerated curing.

The ACI Code also does not address curing requirements for concretes made with other cementitious materials besides portland cement. Since the nature of the cementitious system affects early-age strength development characteristics, this omission may be a major deficiency in the current Code.

Applicability of Curing Practices to High-Performance Concrete

Carino and Meeks (1999) concluded that current curing practices and standards are based on studies related primarily to strength development characteristics of conventional (ordinary) concretes. Most high-performance concretes, however, are fundamentally different from conventional concrete, because they typically have a low water-cementitious materials ratio (*w/cm*) and one or more admixtures. In addition, supplementary cementitious materials, such as silica fume, fly ash, and ground slag, are commonly used in practicable mixtures to achieve high strength, low permeability, reduced temperature rise, and economy. High range water-reducing admixtures are used typically to provide workability. Since the composition of high-performance concrete differs from conventional mixtures, early-age characteristics of the hydrating paste will also differ. Therefore, existing curing practices may not be optimal for high-performance concrete. A better understanding is needed of the role of an external supply of moisture and of the adequacy of membrane-forming compounds when a low *w/cm* is involved.

The effects of *self-desiccation* are also important considerations in high-performance concretes with low *w/cm*. Self-desiccation refers to the process by which concrete dries itself from the inside. Moisture in the paste is consumed by the hydration reactions, and the internal relative humidity may decrease to the point where there is not enough remaining free water to sustain hydration. Consequently, hydration will terminate at an early age if additional moisture is not provided. To prevent early-age self-desiccation, water that is consumed by hydration needs to be replaced by the ingress of external moisture. Therefore, the common practice of sealing concrete with a membrane-forming compound may not be a appropriate curing practice for low *w/cm* concrete. However, for how long is moist-curing effective? As hydration proceeds, capillary pores in the paste become discontinuous, thereby hindering the ingress of additional water into the concrete. When this state is reached, additional moist curing may be of little, or no, benefit, because the water may not be able to penetrate to the interior quickly enough to maintain saturation of the capillaries and sustain hydration. Current curing requirements, based on research on conventional concrete, do not consider these factors.

One of the most controversial topics that emerged from the literature review by Meeks and Carino (1999) concerns the sensitivity of various properties of high-performance concrete to different curing conditions. Some researchers have reported that high-performance concrete is more sensitive to the details of curing than normal concrete; whereas, others have found the opposite to be true, at least for some properties. These differences may be attributed to the different experimental procedures that have been used. For example, Hasni et al. (1994) reported that the use of silica fume makes high-performance concrete more sensitive to different curing methods when considering both strength and durability properties. In addition, they reported that high-performance concrete with silica fume is more sensitive to different curing methods than is normal concrete for characteristics such as compressive and flexural strength, depth of carbonation, and microcracking. Comparison of high-performance concrete without silica fume with normal concrete showed that normal concrete was more sensitive to the curing method for these same properties. With respect to resistance to penetration of chloride ions, results showed that high-performance concretes with and without silica fume, as well as normal concrete, were insensitive to the curing method.

Results of work in Norway that was summarized by Gjørv (1991) generally agree with the findings by Hasni et al. (1994). Gjørv reported that the use of silica fume makes concrete more sensitive to proper curing compared with normal concrete. Silica-fume concrete is more vulnerable to plastic shrinkage cracking than normal concrete, which necessitates good, early-age, curing practices to control this tendency. Another reason cited by Gjørv for why silica-fume concrete is more sensitive to proper curing is related to the effects of drying on strength properties. Good curing practices must be used to prevent early drying, which can reduce tensile and flexural strengths of silica-fume concrete more than for normal concrete.

Torii and Kawamura (1994) also reported on the effects of curing on mechanical and durability-related properties of concrete, and some of their results do not agree with those summarized in the previous paragraphs. Their results indicated that the detrimental effects of poor curing practices on pore structure are more significant in normal-strength concrete than in high-strength concrete with silica fume. In their studies, high-strength concrete in which 8 % of the mass of cement was replaced by silica fume apparently developed a dense pore structure at early ages regardless of curing method. This independence of the curing method is attributed to the use of a low *w/cm* (0.30) and the rapid early-age pozzolanic reactions of the silica fume. Tests for resistance to chloride ion penetration and carbonation depth also showed that high-strength concrete, both with and without silica fume, was less affected by poor curing conditions than normal concrete. This can be attributed to the fact that concrete with a low *w/cm* may attain a low porosity paste at a lower degree of hydration than concrete with a higher *w/cm*. Comparisons between high-strength concretes, with and without silica fume, revealed that the silica-fume concrete was less affected by changes in curing method, when considering resistance to chloride ion penetration and carbonation. Carino and Meeks (1999) conclude that additional studies are needed to reconcile these conflicting conclusions regarding the sensitivity of low *w/cm* concrete to the curing method.

Duration of Curing Period

Hilsdorf and co-workers (Hilsdorf and Burieke 1992; Hilsdorf 1995) have presented informative work on concrete curing. Their efforts include experimental and theoretical studies in the search for rational curing requirements. Although their work was not directed specifically to high-performance concrete, the underlying approaches are applicable to all types of concrete.

According to Hilsdorf and Burieke (1992), concretes can be distinguished by their *curing sensitivity*, which refers to the curing duration needed to reach some specified level of durability or strength. The long-term properties of concrete with low curing sensitivity would not be affected significantly by the duration of the curing period. Curing sensitivity is affected by the characteristics of the cementitious materials, mixture proportions, and the environment to which the concrete is exposed after curing has been terminated. The latter factor affects the rate of moisture loss from exposed surfaces. The *w/cm* of a particular concrete has a significant influence on the curing sensitivity. Concretes with low *w/cm* will gain strength faster and become impermeable sooner than those with higher *w/cm*. This is an important characteristic since it may mean that curing duration can be reduced in accordance with the *w/cm*.

Based on the above considerations, Hilsdorf summarized the four factors that must be considered in establishing minimum curing durations (Hilsdorf 1995):

- Curing sensitivity of the concrete as influenced primarily by the cementitious system;
- Concrete temperature as it affects the rate of hydration (and, therefore, rate of strength development and reduction in porosity);
- Ambient conditions during and after curing as these affect the rate of strength development and severity of drying of the surface layer;
- Exposure conditions of the structure in service as these affect the required "skin" properties for adequate service life.

To establish minimum curing durations, Hilsdorf emphasized that attainment of compressive strength is not the only criterion that must be considered; other possible criteria include the following:

- Depth of carbonation
- Permeability
- Maturity or degree of hydration

The depth of carbonation must be controlled to ensure that the reinforcing steel is surrounded by an alkaline environment and remains in a passive state. The minimum duration of curing for adequate resistance to carbonation depends on the depth of cover, the desired service life, the relationship between time and depth of carbonation, and the relationship between concrete permeability and carbonation. Given this information, additional relationships between permeability, water-cement ratio, and time can be used to estimate the minimum duration of curing (see Meeks and Carino [1999] for a summary). It should be noted that carbonation is not a pervasive problem in North America compared with other regions. This can be attributed, in general, to the deeper cover over reinforcing steel and overall better quality of the concrete in North America.

The permeability criterion is a more general form of the carbonation criterion. In this case, the minimum curing duration is based on achieving a certain level of impermeability as measured by a specific test method. One difficulty in using the permeability criterion is the selection of the critical level of impermeability because there is insufficient knowledge of the relationships between measured permeability values and long-term durability.

In the degree of hydration or maturity criterion, the minimum duration of curing is based on the concrete reaching a specified degree of hydration or maturity. Once the required degree of hydration is defined, empirical relationships between time, temperature, and degree of hydration (or maturity) can be used to estimate the minimum curing duration. The empirical relationships are expected to be affected by the characteristics of the cementitious system in the concrete. As is the case with the permeability criterion, there is insufficient knowledge to relate the minimum degree of hydration (or maturity) at the end of the curing period with long-term performance.

A compressive strength criterion may involve one of two approaches:

1. *R1-Concept*: The concrete is cured until it attains a specified minimum strength. As an example, a suggested minimum strength is the strength after 7 d of moist curing that would be obtained by a reference concrete with a water-cement ratio of 0.6 and made with the same materials as the concrete to be cured (Hilsdorf 1995). A water-cement ratio of 0.6 corresponds closely to the highest value for which capillary pores can become segmented with good curing.
2. *R2-Concept*: The concrete is cured until the in-place compressive strength reaches a prescribed fraction of the 28-day specified compressive strength so that at 28 d the concrete at a prescribed depth will attain the specified strength.

The R1-Concept offers the advantage that the use of mixtures with low water-cement ratios or having rapid early strength development can reduce the curing period. This criterion may be applicable when durability is of concern, because it has been established that, for a given concrete, there is a "reasonably reliable" correlation between compressive strength and other durability-related characteristics (Hilsdorf and Burieke 1992; Ho and Lewis 1988).

In the R2-Concept, the curing duration is independent of the water-cement ratio, but it would depend on the rate of strength development. The R2-Concept is appropriate when structural strength is of concern. The basic notion is that the concrete should be cured long enough so that the in-place strength at some depth below the surface attains the specified strength used to design the structure. This is illustrated schematically in Fig. 1, where the solid curve represents strength development of the concrete under standard curing and the dashed curve represents in-place strength development at some prescribed distance from the exposed surface. When curing is terminated, drying of the surface occurs and hydration ceases when the moisture content in the surface layer falls below a critical value. However, it will take time for the drying front to penetrate into the concrete. As result, the interior concrete continues to gain strength after curing is terminated. When the drying front reaches the prescribed depth, two things happen: (1) the strength increases due to drying and (2) the rate of hydration is reduced. Later, the concrete at the prescribed depth dries below a critical level and strength development ceases. The objective is to ensure that the two strength development curves cross at an age of 28 d or later.

The question that has to be answered to implement the R2-Concept is as follows: What fraction of the standard-cured strength has to be attained at the end of the curing period to ensure that the design strength is attained in the interior of the member? ACI Committee 308 (1998) specifies that the strength at the end of the curing period should be at least 0.7 of the design strength. Hilsdorf (1995) notes that this value is based on data obtained in the early 1950s, and those results may not be applicable to modern concretes. Hilsdorf suggests that a value of 0.7 may be conservative, and that research is needed to understand the dynamics of internal drying and strength development after curing is terminated for different types of modern concretes.

Hilsdorf (1995) suggested that the curing period should be long enough so that at 28 d (or other applicable age) the concrete strength at the depth of the first layer of reinforcement will equal the design strength. The rationale for this requirement is to ensure that the bond strength (or development length) of the reinforcing steel will attain the value assumed in the structural design. Hilsdorf used analytical models to estimate the required curing duration. Diffusion theory was used to model the drying of the concrete from the exposed surface. It was assumed that the rate of hydration was not affected until the moisture content dropped below the value that is in equilibrium with a relative humidity of 90 %. The calculations were carried out for a concrete with a 28-day strength of 40 MPa, for cements with different hardening rates, and for different values of ambient relative humidity (ambient temperature was 20 °C). The cover depth was taken conservatively as 25 mm. The results of the calculations are summarized in Fig. 2.

The vertical axis in Fig. 2 represents the fraction of the standard-cured, 28-day strength when curing is terminated. The horizontal axis represents the 28-day strength at a depth of 25 mm expressed as a fraction of the 28-day design strength. The effects of different cement types were minor (see Hilsdorf 1995), and so the results of the calculations are shown as three curves, each representing a different ambient relative humidity. Based on these calculations, for an ambient relative humidity of 60 %, curing may be terminated when the concrete has attained 0.6 of the standard-cured, 28-day strength. If the ambient relative humidity is 50 %, curing has to be maintained until 0.85 of the standard-cured strength is attained. On the other hand, if the ambient relative humidity is 80 %, only about 0.4 of the standard-cured strength has to be attained. The time required to achieve these fractional strengths at a specific temperature can be estimated from the strength development characteristics of the cement.

In summary, Hilsdorf and co-workers presented a rational approach to establish the curing duration. A key factor affecting this duration is the controlling criterion for adequate long-term performance. Hilsdorf's studies showed that, in most cases, the critical curing duration was controlled by compressive strength criteria (Hilsdorf and Burieke 1992; Hilsdorf 1995). This is an important finding because it tends to affirm that strength-based criteria may be the most practical approaches to evaluate the adequacy of curing, possibly even when durability is a primary concern. If preliminary testing of the specific concrete mixture to be used in construction results in a reliable correlation between strength and durability, in-place strength measurements would be a suitable method for assessing the adequacy of curing in the field.

OBJECTIVE AND SCOPE

The exploratory study summarized in this paper examines the influence of the duration of moist curing on the variation of strength with distance from the drying surface. The strength at an age of 28 d was used as the basis for comparison. To simplify testing, mortar was used instead of concrete and only portland cement was used as the cementitious material. While these simplifications may limit the direct applicability of the results, it was felt that correct trends would be revealed.

Two mortar mixtures with water-cement ratios of 0.30 and 0.45 were used; the former is intended to be representative of the hydration and drying behavior of a high-performance concrete with a low *w/cm*. Three moist curing periods were used: (1, 3, or 7) d. At the end of the moist-curing period, the specimens were sealed and allowed to dry at 25 °C at either 50 % or 70 % relative humidity (RH). Reference specimens were continuously moist cured by storing them in a limewater bath.

Tensile strength was measured at 28 d as a function of distance from the drying surface using cylindrical test specimens with circular notches cast at various depths. The notches created reduced cross sections that forced failures to occur at predetermined distances from the drying surface. The estimated average tensile strength at a depth of 25 mm was used as the basis for evaluating the influence of the different curing procedures. The objective was to determine the minimum duration of moist-curing so that the 28-day strength at 25 mm was not lower than the case of continuous moist-curing.

Six curing treatments, in addition to continuous moist curing, were investigated for each water-cement ratio. Four notch depths were used for each treatment. Three replicate specimens were tested for each notch depth. For the continuously moist-cured specimens, two runs were used to establish the reproducibility of the results. Additional details of the experimental program may be found in the doctoral dissertation of the second author (Meeks 1997) and a summary report by Carino and Meeks (2000).

EXPERIMENTAL PROCEDURE

Table 1 lists the mixture proportions of the two mortars used to prepare the cylindrical specimens. The two mixtures were proportioned so that they had approximately the same volume fraction of paste. The water in the high-range water reducer was included as part of the mixing water. The sand was a graded silica sand that conformed to ASTM C 778. The portland cement was a sample of cement 116 issued by the ASTM Cement and Concrete Reference Laboratory (CCRL) in its proficiency sample program. Table 2 lists the degree of hydration versus age for curing of CCRL cement 116 under saturated conditions. These data were obtained from the difference in mass measurements at 105 °C and 950 °C (Bentz 1997). Note that for the $w/c = 0.30$ paste, the long-term degree of hydration is about 70 % because there is insufficient capillary porosity to accommodate the reaction products corresponding to complete hydration.

The mortars were mixed in accordance with ASTM C 305. Plastic pipe with a nominal inside diameter of 50 mm was used to construct cylindrical molds with a length of about 125 mm. As shown in Fig. 3, each mold included a 5 mm thick ring with an inside diameter of about 40 mm. The ring created a reduced cross sectional area of about 64 % of the full cross section. The rings were positioned at depths of (10, 20, 30 and 40) mm from the top surface. Each mold was filled in three layers, and consolidated with a rubber tamper plus a vibrating table to reduce the number of large air voids (see Meeks 1997). The top surface was smoothed with a trowel. At approximately 75 minutes from the start of mixing, the specimens were submerged carefully into a lime-saturated water bath at 23 ±2 °C.

Figure 4 summarizes the experimental procedure. At the end of the designated period of moist curing, the molds were removed and the bottoms and sides of the cylinders were covered with plastic "duct" tape so that subsequent drying would occur only from the top surface. The masses of the sealed specimens were measured, and the specimens were placed in the drying chambers. The masses of the drying specimens were measured periodically. At an age of 27 d the cylinders were prepared for tensile testing. The tape was removed from the cylinder bottoms, and the ends were sand blasted to expose clean surfaces. For the continuously moist-cured cylinders, the specimens were removed from the water bath and the sides were sealed with tape prior to sand blasting. Steel disks, 12.5 mm thick and with a central threaded hole, were bonded to the ends of the cylinders using a high-strength, structural grade epoxy. Precautions were taken to ensure that the disks were aligned properly with respect to the cylinders (Meeks 1997). The epoxy was allowed to cure overnight.

On the 28th day, the specimens were tested in uniaxial tension. Tensile load was applied by a hydraulically-operated testing machine. The load was transferred to the disks through a "hook and eye" linkage to reduce bending (Meeks 1997; Carino and Meeks 2000). Load was applied by constant movement of the machine cross head so that the applied stress rate in the linear portion of the tests was 3.5 ± 0.15 kPa/s. After testing was completed, the disks were removed carefully with a hammer and chisel, and the top portion of the cylinders were split in half using the splitting-tension loading method. The exposed surfaces were examined visually to estimate the depths of the drying fronts (indicated by the lighter shade). The drying front was more difficult to observe in the $w/c = 0.45$ specimens because of their generally lighter shade compared with the $w/c = 0.30$ specimens.

RESULTS

The individual results of the tensile tests are reported in Carino and Meeks (2000) and shown here using scatter plots. Commercial statistical analysis software was used to establish relationships between the measured tensile strengths and the depth of the failure surface, and to determine confidence intervals for the estimated average strength at a depth of 25 mm. The results for the continuously moist-cured specimens are used as the bases for comparisons.

Continuously Moist-Cured Specimens

There were two runs for the w/c = 0.30 and w/c = 0.45 specimens that were cured under water continuously for 27 days. The two runs were used to establish the details of the testing procedure and the batch-to-batch repeatability. In all cases except one, the failure plane was at the reduced cross section nearer to the top surface of the cylinder. With few exceptions, the coefficient of variation of replicate tests was found to be about 10 % or less. This is not unreasonable for a direct tensile strength test that is more sensitive to testing errors than the typical compressive strength tests. Some individual test results were identified as outliers as is explained below.

Figures 5(a) and 6(a) show the individual test results plotted as a function of the nominal depth of the failure surface. Contrary to expectation, there appears to be a tendency for increasing strength with distance from the top surface. To examine whether this trend is statistically significant, it was first necessary to establish whether the data for the two runs could be combined for the purpose of regression analysis. A linear fit was assumed and an F-test was used to compare the sum of the squares of the residuals for a separate regression for each run with the residuals for a single regression for both runs grouped together. See Carino et al. (1983) for the procedure to carry out this F-test. For each w/c, the results of the F-tests indicated insufficient evidence to reject the null hypothesis (no difference between the lines). Thus for each w/c, one line was fitted to the combined data from the two runs.

The presence of outliers was examined by using normal probability plots of the residuals for the best-fit lines to all the data points. Figure 5(b) and 6(b) show the normal probability plots of the residuals when all points for each w/c were considered in fitting straight lines. If the residuals are normally distributed, which is a fundamental assumption of regression analysis, they should plot approximately along a straight line in a normal probability plot.

w/c = 0.30—As shown in Fig. 5(b), when all data points are used, there are three points with large negative residuals that deviate from the straight line that would be defined by the remaining residuals. These three points were, therefore, considered as outliers and disregarded. Figure 5(a) shows the best-fit line to the combined data with outliers removed. The equation of the line is:

$$Y\,(\mathrm{MPa}) = 3.55\ \mathrm{MPa} + 0.053\ \mathrm{MPa/mm}\ X \qquad (1)$$

The residual standard deviation of the fit is 0.36 MPa. The slope of the line is 0.053 MPa/mm, and this value was found to be statistically significant ($p < 0.0001$). The probability "p" in this case represents the likelihood that the calculated slope is due to chance. Thus a low value of "p" means it is unlikely that the calculated slope is due to chance. As is the custom, a probability value of less than 0.05 is adopted as an indicator of statistical significance. Figure 5(a) also shows, as dashed lines, the 95 % confidence limits for the *average* strength as a function of depth. These confidence limits are used in subsequent data analyses as the basis for comparing the results for the various curing and drying regimens. Based on the straight-line relationship, the estimated average tensile strength at a depth of 25 mm is 4.88 MPa, with a 95 % confidence interval of 4.72 MPa to 5.05 MPa.

w/c = **0.45**—The normal probability plot of the residuals in Figure 6(b) shows that, when a straight line is fitted to all of the w/c = 0.45 data, the residuals fall approximately on a straight line with the exception of two points. These two points were considered, therefore, as outliers and were disregarded. Figure 6(a) shows the best-fit straight line to the combined data with the two outliers removed. The equation of the line is:

$$Y\,(\mathrm{MPa}) = 2.53\ \mathrm{MPa} + 0.016\ \mathrm{MPa/mm}\ X \qquad (2)$$

The residual standard deviation of the best-fit line is 0.29 MPa The value of the slope is 0.016 MPa/mm, and this value was found to be statistically significant ($p = 0.0008$). The estimated average strength at a depth of 25 mm is 2.94 MPa, with a 95 % confidence interval of 2.81 MPa to 3.08 MPa.

In summary, the results for the specimens that were continuously moist cured indicate increasing tensile strength with distance from the top surface of the cylinders. This may be related to two factors:

- The presence of bleed water would tend to reduce the strength of the upper layer because this bleed water is mixed within the mortar during consolidation of the upper layers.
- The lower layers are more densely compacted than the upper layer.

Such a strength variation with depth of concrete members is well known (Bartlett and MacGregor 1999).

1 Day Moist-Cured Specimens

The individual tensile strengths for specimens that were moist cured for 1 day are shown in Figs. 7 and 8. Some cylinders had failure planes at the bottom of the rings (see Fig. 4), and these are shown as depths of (15, 25, 35, and 45) mm. Missing data points are a result of failures near the bond line between the mortar and steel disk. Regression analysis was used to examine the variation of tensile strength with depth for each condition (water-cement ratio and relative humidity after moist curing).

w/c = 0.30—Figure 7(a) shows the strength versus depth results for *w/c* = 0.30 and drying at 50 % RH. Regression analysis indicated that the slope was not statistically significant ($p = 0.28$). The best-fit line is shown using long dashs. A normal probability plot of the residuals about the best-fit line indicated no outlying points. Since the slope of the line is not statistically significant, an overall average strength was computed. This overall average strength for all depths is 4.75 MPa, which is shown as a solid line in Fig. 7(a). The standard error (standard deviation divided by the square root of the number of points) of the overall average is 0.11 MPa. Therefore, the 95 % confidence interval for the overall average strength is 4.51 to 4.99 MPa, which is shown in Fig. 7(a) by the error bars for the point (open circle) at 25 mm. Also shown in Fig. 7(a) is the 95 % confidence interval for the estimated average strength as a function of depth that was obtained for the continuously moist-cured specimens (Fig. 5(a)). It is clear that there is a difference between the strength-depth relationships of the continuously moist-cured specimens and those moist cured for 1 d. The average strength, however, of 4.75 MPa for the specimens with the 1 d of moist curing is within the 95 % confidence interval of the estimated strength at 25 mm obtained from the continuously moist cured specimens.

Figure 7(b) shows the results for the *w/c* = 0.30 specimens exposed to drying at 70 % RH after 1 d of moist curing. The slope of the best-fit line was also not statistically significant ($p = 0.83$). A normal probability plot of the residuals revealed that two points had large deviations from the straight line defined by the rest of the residuals. These points are indicated as "outliers" in Fig. 7(b), and were not considered in the final analysis. The overall average of the remaining strengths is 4.70 MPa with a standard error of 0.11 MPa. Therefore, the 95 % confidence interval of the overall average strength is 4.46 MPa to 4.94 MPa, which overlaps the 95 % confidence interval of 4.72 MPa to 5.05 MPa for the average strength at 25 mm for the continuously moist-cured specimens.

Comparison of the 95 % confidence intervals of the average strengths for the specimens that were allowed to dry at 50 % RH with those allowed to dry at 70 % RH shows that they are nearly the same. Thus there was no statistically significant difference in the results for the two drying conditions.

***w/c* = 0.45**—Figures 8(a) and (b) show the 28-day strengths for the *w/c* = 0.45 specimens stored at 50 % and 70 % RH, respectively, after 1 d of moist curing. The results are similar to those for the *w/c* = 0.30 specimens. Regression analyses indicated that the slopes were not statistically significant ($p = 0.82$ for 50% RH and $p = 0.74$ for 70 % RH). In addition, there were no obvious outliers. For drying at 50 % RH, the overall average strength is 3.16 MPa, the standard error is 0.11 MPa, and the 95 % confidence interval for the average strength is 2.92 MPa to 3.38 MPa. For drying at 70 % RH, the corresponding values are 3.24 MPa, 0.09 MPa, and 3.04 MPa to 3.44 MPa. Since the confidence intervals for the average strengths overlap, there is no statistically significant difference between the results for the two drying conditions. Figures 8(a) and 8(b) also show the 95 % confidence intervals for the average strength versus depth relationship obtained from the continuously moist-cured specimens (Fig. 6(a)). While the 1-day moist-cured specimens tend to have a higher average strength than the estimated strength of 2.94 MPa at 25 mm for the continuously moist-cured specimens, the overlapping 95 % confidence intervals shown in Figs. 8(a) and 8(b) indicate that the differences are not statistically significant.

In summary, the results for the specimens that were moist-cured for 1 d prior to exposure to drying indicate that sufficient 28-day strength was attained at a depth of 25 mm in comparison with the specimens that were continuously moist cured. An unexpected result is that the measured strengths at a depth of 10 mm tended to be greater than the corresponding strengths in the continuously moist-cured specimens. It was expected that the short period of moist curing followed by drying would hinder hydration and result in lower strengths compared with continuous moist curing. However, it is well known that cementitious materials become stronger as they dry out (Bartlett and MacGregor 1994). Thus it is possible that the increase in strength due to drying compensated for any strength reduction due to reduced hydration. Verification of this hypothesis would require testing specimens at later ages than used in this exploratory study.

3 Day Moist-Cured Specimens

Figures 9 and 10 show the 28-day tensile strengths for the specimens that were moist cured for 3 days. There is a missing value at 30 mm in Fig. 9(a) due to a testing error.

w/c = 0.30—Figure 9(a) shows the individual test results for the *w/c* = 0.30 specimens that were stored at 50 % RH. The results show more scatter than the previous results for the 1-day moist cured specimens. The low strength of 2.79 MPa for the 40 mm depth was considered to be an outlier and was excluded from the analysis. That specimen was found to have a large air void within the failed cross section (Meeks 1997). Regression analysis showed that the slope was not statistically significant ($p = 0.39$). The overall average tensile strength is 4.57 MPa with a standard error of 0.22 MPa. The 95 % confidence interval for the average strength is 4.07 MPa to 5.07 MPa. Figure 9(a) shows that the confidence interval for the overall mean overlaps the confidence interval for the estimated strength at 25 mm based on the continuously moist-cured specimens.

Figure 9(b) shows the individual test results for the specimens stored at 70 % RH. The data are less scattered. The low strength of 4.17 MPa for the 40 mm depth was considered to be an outlier and excluded from the analysis. It also had a large air void within the failure cross section (Meeks 1997). Again, the slope is not statistically significant ($p = 0.16$), and the overall average tensile strength is 5.22 MPa with a standard error of 0.06 MPa. The 95 % confidence interval for the average strength is 5.08 MPa to 5.35 MPa, which does not overlap the interval for the estimated average strength at 25 mm obtained from the continuously moist-cured specimens. Thus these results show that the $w/c = 0.30$ specimens exposed to 70 % RH after 3 days of moist-curing had higher 28-day strength at 25 mm than the specimens that were moist-cured continuously.

Statistical comparison of the overall average tensile strength for the specimens stored at 50 % RH with those stored at 70 % RH indicated a statistically significant difference ($p = 0.008$). Thus the specimens allowed to dry at 50 % RH were, on average, weaker

w/c = **0.45**—Figure 10(a) shows the 28-day tensile strengths for the $w/c = 0.45$ specimens stored at 50 % RH. In contrast with the previous results, regression analysis indicated that that the slope was statistically significant ($p = 0.021$). The slope, however, was negative and strength decreased with depth. From the best-fit line, the estimated average strength at 25 mm is 3.36 MPa, with a 95 % confidence interval of 3.23 MPa to 3.49 MPa. As seen in Fig. 10(a), the 28-day average strength at 25 mm is higher for the specimens allowed to dry after 3 days of curing than for the continuously moist-cured specimens.

Figure 10(b) shows similar results for the specimens allowed to dry at 70 % RH. The negative slope is statistically significant ($p = 0.012$), and the estimated average strength at 25 mm is 3.52 MPa with a 95 % confidence interval of 3.39 MPa to 3.65 MPa.

The confidence intervals of the estimated strength at 25 mm for the two drying conditions overlap. Thus there is no statistically significant difference due to relative humidity.

Examination of Figs. 10(a) and 10(b) shows that the statistically significant negative slopes are due primarily to the slightly higher strengths at 10 mm compared with the strengths at the other depths. These higher strengths are attributed, again, to the increase in strength due to drying.

7 Day Moist-Cured Specimens

Figures 11 and 12 show the 28-day strengths of the specimens that were moist cured for 7 days prior to drying. There are no missing data points, and no points were identified as outliers.

w/c = **0.30**—Figure 11(a) shows the results for the $w/c = 0.30$ specimens dried at 50 % RH. Linear regression indicated that the slope was not statistically significant ($p = 0.65$). The overall average tensile strength is 5.13 MPa, the standard error is 0.12 MPa, and the 95 % confidence interval is 4.87 MPa to 5.40 MPa. This interval overlaps the confidence interval of the estimated strength at 25 mm for the continuously moist-cured specimens. Thus the strength at 25 mm for the 7-day cured specimens is similar to that of the continuously moist cured specimens.

Figure 11(b) shows the results for the specimens dried at 70 % RH. The behavior differed from the other cases. The strengths of the specimens with reduced sections at 10-mm were lower than similar w/c = 0.30 specimens subjected to drying. These strengths, however, are in good agreement with those obtained from the continuously moist cured specimens. Therefore, the lower strength could be due to the "top-to-bottom" effect if the drying front did not penetrate beyond 10 mm. There is, however, some uncertainty about the strengths of the two specimens that failed at 10 mm (Meeks 1997). When they were originally tested, failure occurred near the steel-epoxy interface. New steel discs were bonded to the ends of the specimens and the specimens were re-tested. Some damage could have occurred during the first loading. Thus it is not possible to state with certainty whether the strength at 10 mm is lower in this case compared with the other w/c = 0.30 specimens exposed to drying. If the measured strengths at 10 mm are assumed to be valid values, the slope of the best-fit line is statistically significant (p = 0.007). The estimated average strength at 25 mm is 4.61 MPa with a 95 % confidence interval of 4.39 to 4.81 MPa. Figure 11(b) shows that this interval overlaps the interval for the estimated average strength based on the continuously moist-cured specimens.

w/c = **0.45**—Figure 12(a) shows the 28-day tensile strength for the w/c = 0.45 specimens exposed to drying at 50% RH after 7 days of moist curing. The best-fit line has a slope that is on the borderline of being statistically significant (p = 0.058). If the line is assumed to represent the variation of strength with depth, the estimated strength at 25 mm is 3.31 MPa with a 95 % confidence interval of 3.14 MPa to 3.48 MPa. As seen in Fig. 12(a), this confidence interval lies slightly above the interval for the estimated average strength at 25 mm for the continuously moist-cured specimens. Not also that the three measured strengths at 25 mm are in good agreement with the confidence interval of the moist-cured specimens.

Finally, Fig. 12(b) shows the results for the specimens exposed to drying at 70 % RH. The slope of the best-fit line was not statistically significant (p = 0.75). The overall average strength is 3.33 MPa, the standard error is 0.09 MPa, and the 95 % confidence interval is 3.14 MPa to 3.52 MPa. This confidence interval is also slightly higher than the interval for the strength at 25 mm for continuous moist curing.

The similarity in the confidence intervals for the estimated average strength at 25 mm for the two drying conditions shows that relative humidity did not have a significant effect.

SUMMARY

This exploratory study examined the influence of the duration of moist curing on the variation of 28-day strength with distance from the drying surface. The objective was to determine the duration of moist curing so that the strength at 25 mm from the exposed surface would not be less than the corresponding strength for the case of continuous moist curing (reference condition). Table 3 summarizes the 95 % confidence intervals for the estimated, average 28-day strength at 25 mm from the exposed surface. The last column of Table 3 indicates the nature of the measured relationships between strength and depth. A "+" indicates that the strength increased with depth, a "-" indicates that strength decreased with depth, and a "0" indicates no relationship between strength and depth.

Figure 13 is a graphical representation of the confidence intervals in Table 3. The horizontal dashed lines are the 95 % confidence intervals for the estimated strength at 25 mm obtained from the continuously moist-cured specimens. The results show that for the various treatments in no case was the strength at 25 mm significantly lower (from a statistical viewpoint) than for the case of continuous moist curing. In fact in some cases, the strength was greater than for the reference condition. These results were unexpected, especially for the 1-day duration of moist curing. It was anticipated that a short duration of moist curing would result in rapid drying and a decrease in the hydration rate. As explained in the previous section, the increase in strength due to the physical process of drying may have compensated for any reduction due to a decrease in the degree of hydration. Figure 13 also shows that the relative humidity during the drying period did not have a consistent and statistically significant effect.

Additional insight into the reason for the observed behavior summarized in Fig. 13 is given in Table 4. As mentioned, some of the specimens were split after tensile testing to visually observe the depth of the drying front. While these measurements are approximate, the results appear to show that, for the testing period of 28 days used in this study, the drying front never penetrated to a distance of 25 mm.

Based on these tests of mortar specimens, it could be concluded that only 1 d of moist curing is sufficient to ensure adequate strength development at 25 mm from the exposed surface for the water-cement ratios and drying conditions that were used. These results may explain why extended curing has typically not been considered a major concern with regard to structural capacity of reinforced concrete.

Since the study focused on the effects of duration of moist curing on strength, the results should not be extrapolated to mean that short curing periods are also adequate for durability. The mass losses of the mortar specimens during drying provide some insight into the effects of curing duration on potential durability. Parrot (1992, 1996) demonstrated that moisture loss during the first 4 d after termination of moist curing was a good indicator of subsequent durability properties, such as water sorptivity. In this study, the moisture loss at 5 d after the end of moist curing is used as a basis for comparison. The 5-day mass loss is used because this was the common drying time for which all specimens had a moisture loss measurement (Meeks 1997). Figure 14(a) shows the 5-day mass loss for all the test specimens. Mass loss is expressed in terms of reduction in mass per unit area of exposed surface. One of the data points was identified as an outlier, as indicated in Fig. 14(a). Figure 14(b) shows the average 5-day mass loss per unit area and the corresponding 95 % confidence intervals. Several observations can be made:

- The average moisture losses for drying at 50 % RH were greater than for drying at 70 % RH.
- The greater the duration of moist curing, the lower the moisture loss.
- An increase in the duration of moist curing from 1 d to 3 d resulted in a drastic decrease in the moisture loss for the $w/c = 0.45$ specimens.

The first two observations are not very revealing, as these are well known phenomena. The third observation, however, is of particular interest because it shows that, from a durability viewpoint, mixtures with higher w/c benefit more from extended moist curing than mixtures with lower w/c. This is not surprising, because more than 40 years ago Powers et al. (1959) noted that as the w/c increases more hydration is required to disrupt the continuity of capillary pores. Similar conclusions about curing duration were reached for the durability-related curing criteria of Hilsdorf and co-workers (Hilsdorf and Burieke 1992; Hilsdorf 1995).

As is common with exploratory studies, this work raised questions that merit further investigation. Tests are underway to repeat these experiments, but using measurement of degree of hydration as a function of depth. This will avoid the problem of increasing strength due to drying that may have confounded the results reported here. Similar studies were conducted by Kern et al. (1995) for concrete with $w/c = 0.60$ and ages up to 7 d. The results from these new tests should provide a clearer understanding of the effects of the duration of curing and subsequent exposure conditions on the variation of degree of hydration with distance from the exposed surface. The investigation will be extended to include mixtures containing supplementary cementitious materials. The long-term objective of the research is to develop a verified numerical model that will permit investigation of the many factors that affect the required duration of curing. The results of that investigation should provide the knowledge to formulate rational curing guidelines for high-performance concrete.

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TABLE 1—MASS PROPORTIONS OF MORTAR MIXTURES

	w/c = 0.30	w/c = 0.45
Water	0.278	0.450
Cement	1.000	1.000
Sand	2.207	2.750
HRWR	0.036	0.006

TABLE 2—DEGREE OF HYDRATION VERSUS AGE FOR CCRL CEMENT 116 CURED UNDER SATURATED CONDITIONS AT 25 °C

Age, d	Degree of Hydration, %		
	w/c = 0.30	Age, d	w/c = 0.45
0.33	13.7	0.33	15.4
1.00	**39.1**	**1.00**	**41.7**
2.00	50.9	2.00	51.9
3.00	**56.3**	**3.00**	**58.4**
7.00	**62.0**	**7.00**	**71.7**
14.00	65.5	14.00	78.8
27.96	68.9	27.96	83.1
28.17	69.9	27.96	80.1
54.00	69.9	56.00	82.7
90.00	68.7	91.00	87.5

TABLE 3—SUMMARY OF ESTIMATED 95 % CONFIDENCE INTERVALS OF AVERAGE STRENGTH AT 25 mm

w/c	Moist Curing, d	RH, %	Average Strength, MPa	Strength vs. Depth†
0.30	Continuous		4.88 ±0.17	+
	1	50	4.75 ±0.24	0
		70	4.70 ±0.24	0
	3	50	4.57 ±0.50	0
		70	5.22 ± 0.14	0
	7	50	5.13 ±0.27	0
		70	4.61 ±0.21	+
0.45	Continuous		2.94 ±0.14	+
	1	50	3.16 ±0.23	0
		70	3.24 ±0.20	0
	3	50	3.36 ±0.13	-
		70	3.52 ±0.13	-
	7	50	3.31 ±0.17	-
		70	3.33 ±0.19	0

† "0" indicates no relationship between strength and distance from the drying surface, "+" indicates strength increased with depth, and "–" indicates that strength decreased with depth

TABLE 4—OBSERVED APPROXIMATE DEPTH OF DRYING FRONT (mm), (Meeks 1997)

Moist	w/c = 0.30		w/c = 0.45	
Curing, d	50 % RH	70 % RH	50 % RH	70 % RH
1	14	11	NM*	14
3	10	8	NM	12
7	NM	6	14	12

*NM = not measured

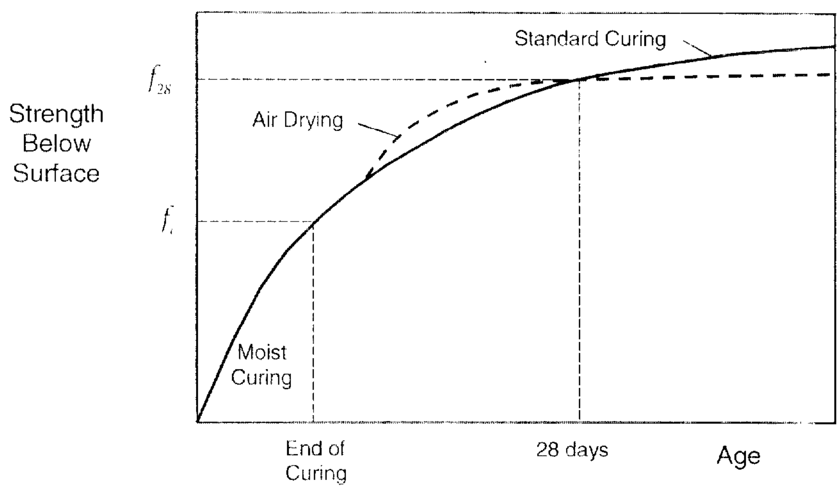


Fig. 1–Schematic of strength development below surface for standard curing and for moist curing followed by air drying

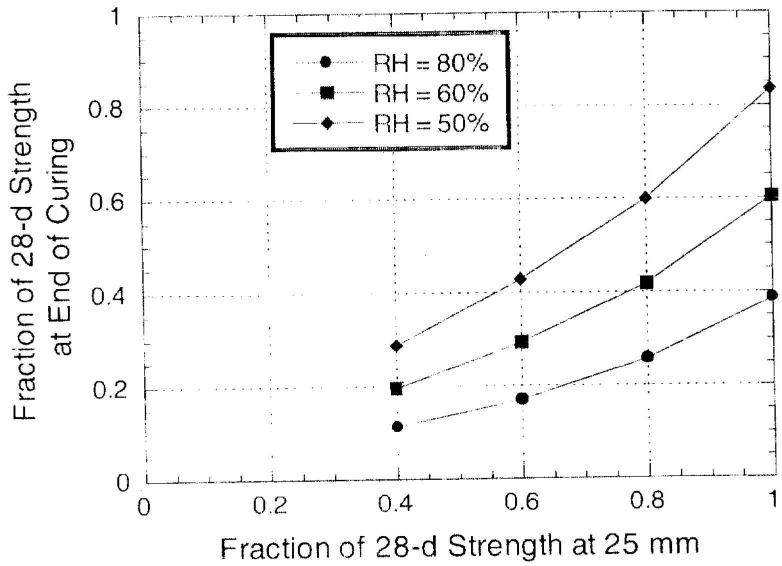


Fig. 2–Relationships between strength ratio at depth of 25 mm and ratio of strength at end of curing period (based on figure provided by H.K. Hilsdorf)

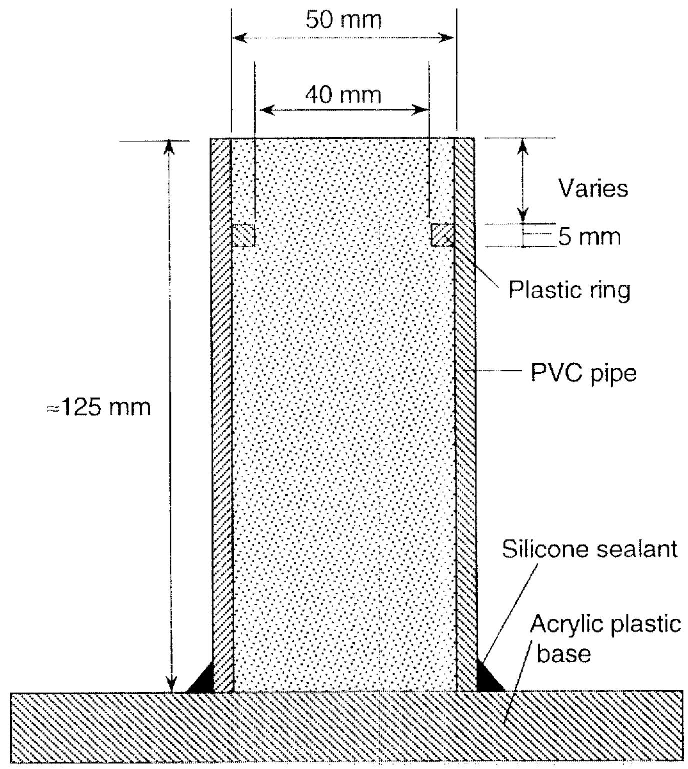


Fig. 3–Mold used to prepare notched, cylindrical tension specimen

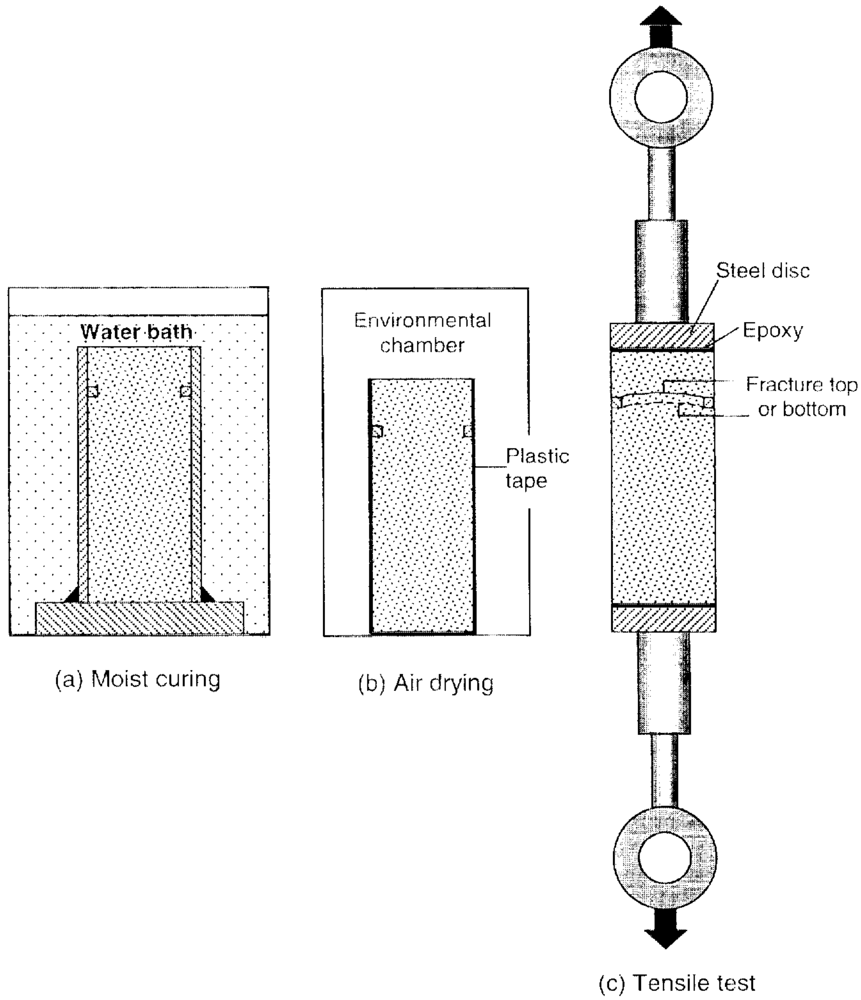
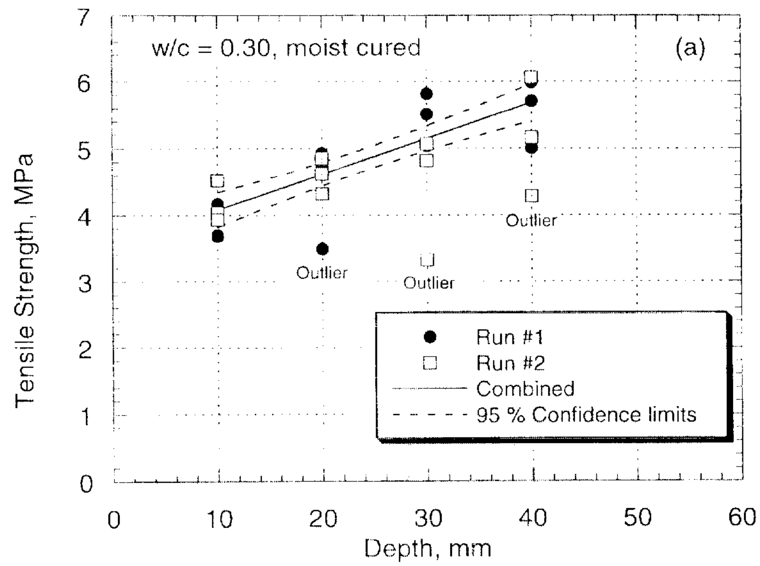


Fig. 4–Curing, drying, and testing of mortar cylinders



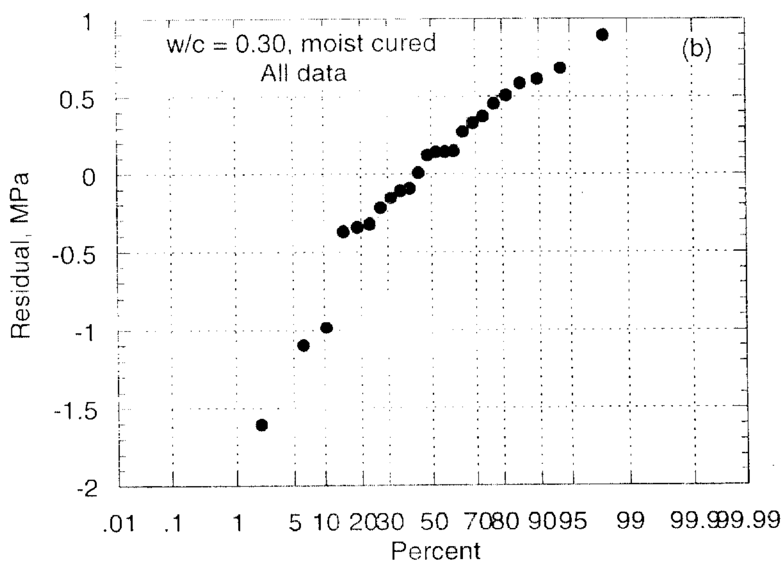


Fig. 5–(a) Tensile strength versus depth for continuously moist-cured specimens with *w/c* = 0.30; (b) normal probability plot of residuals for straight line fit using all data

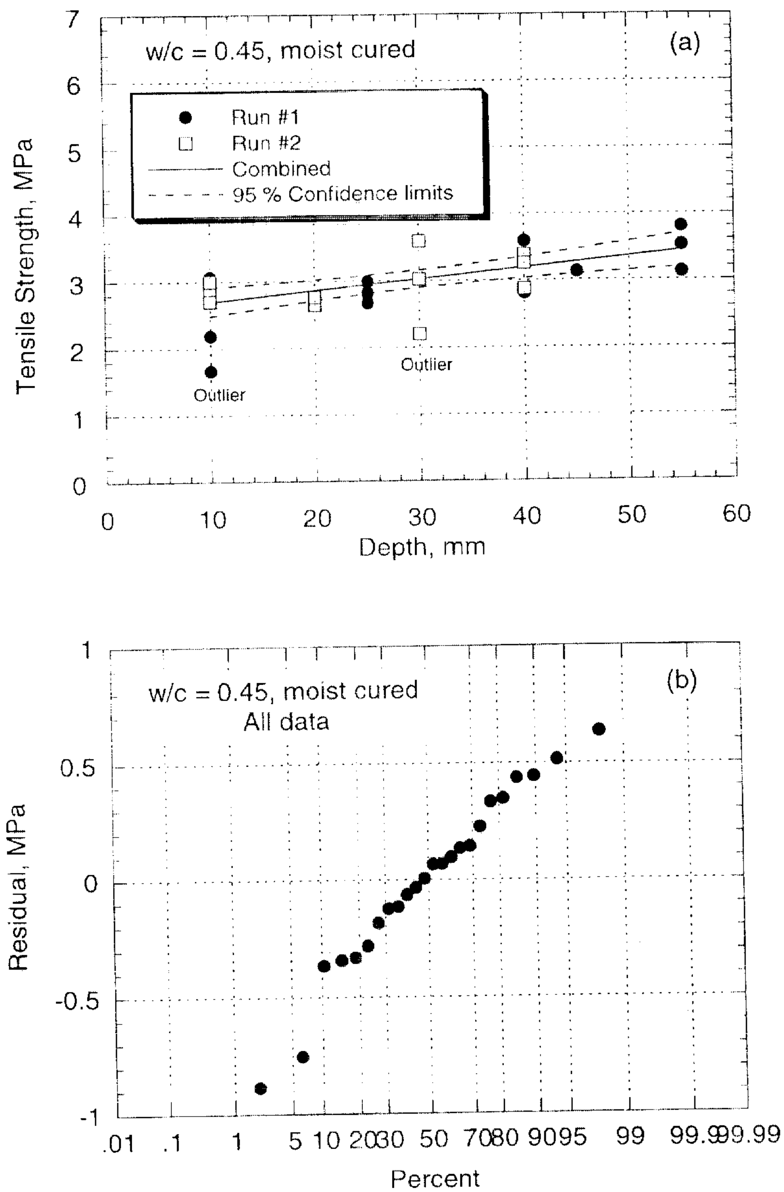


Fig. 6–(a) Tensile strength versus depth for continuously moist-cured specimens with *w/c* = 0.45; (b) normal probability plot of residuals for straight line fit using all data

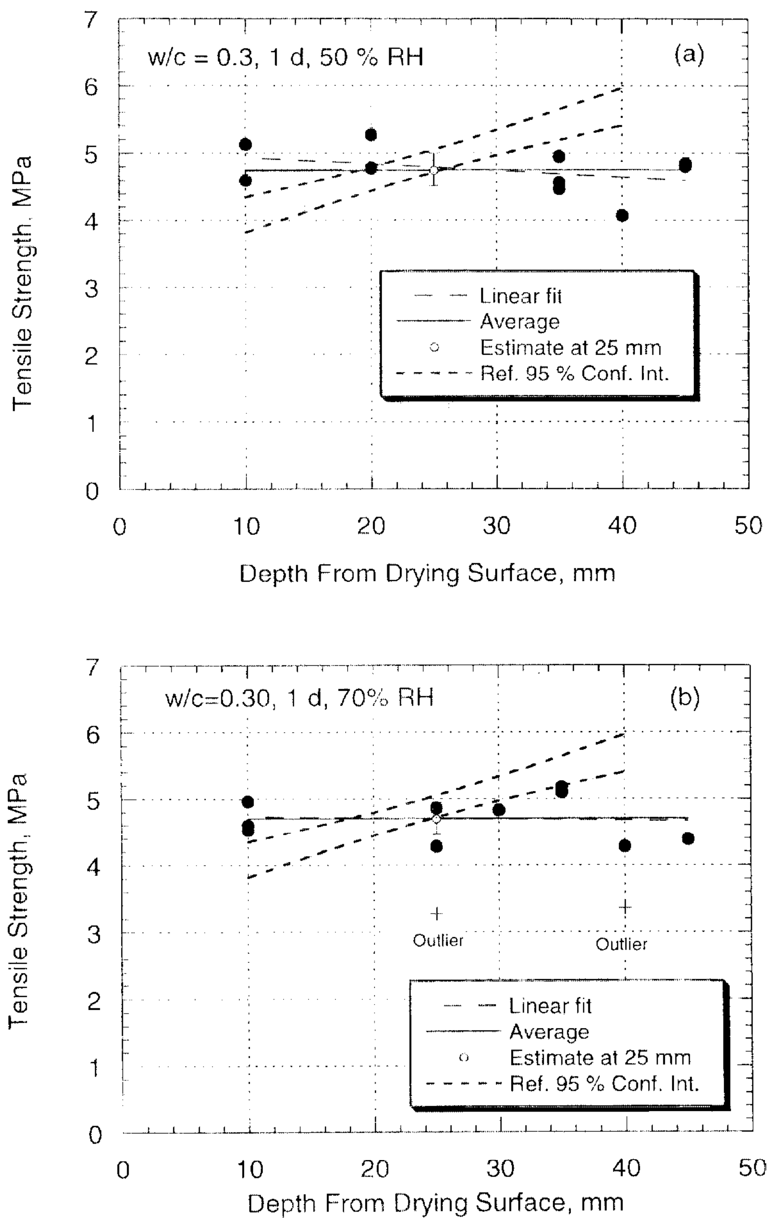
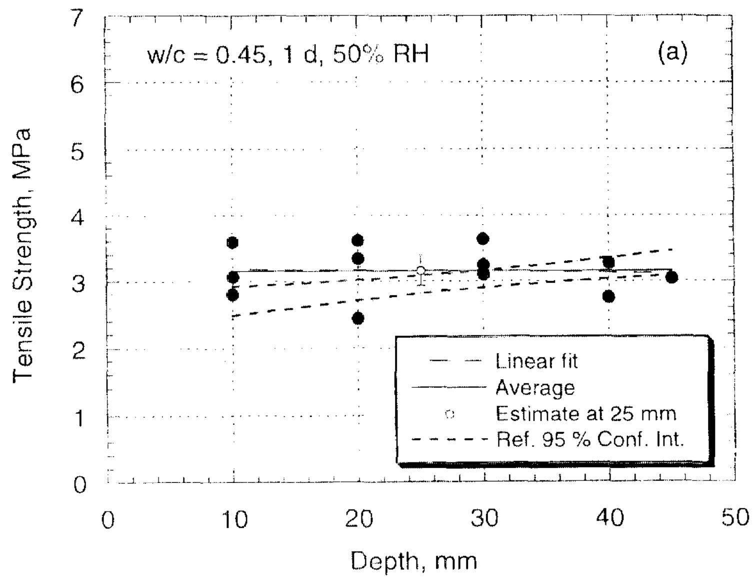


Fig. 7–Tensile strength versus depth for *w/c* = 0.30 with 1 day of moist curing followed by: (a) drying at 50 % RH and (b) drying at 70 % RH



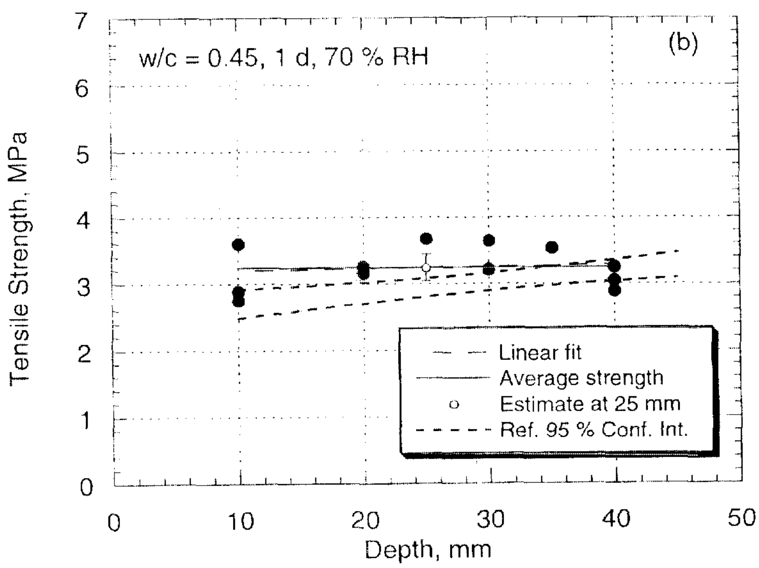
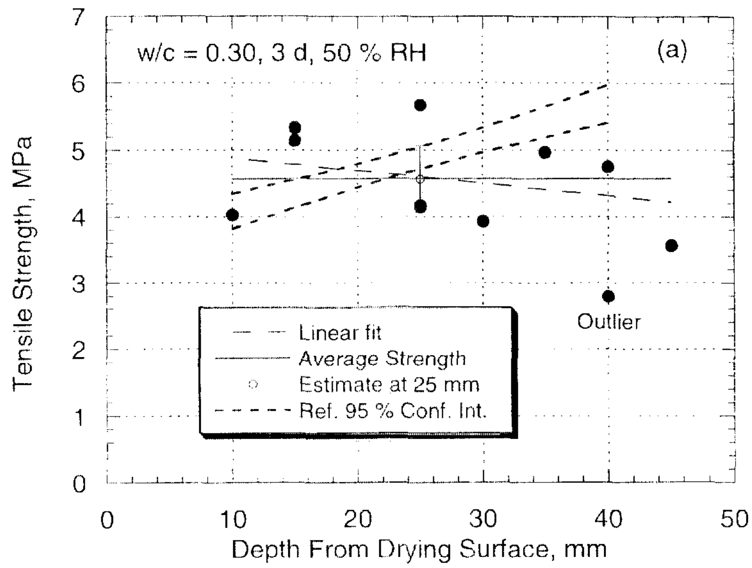


Fig. 8–Tensile strength versus depth for *w/c* = 0.45 with 1 day of moist curing followed by (a) drying at 50 % RH and (b) drying at 70 % RH



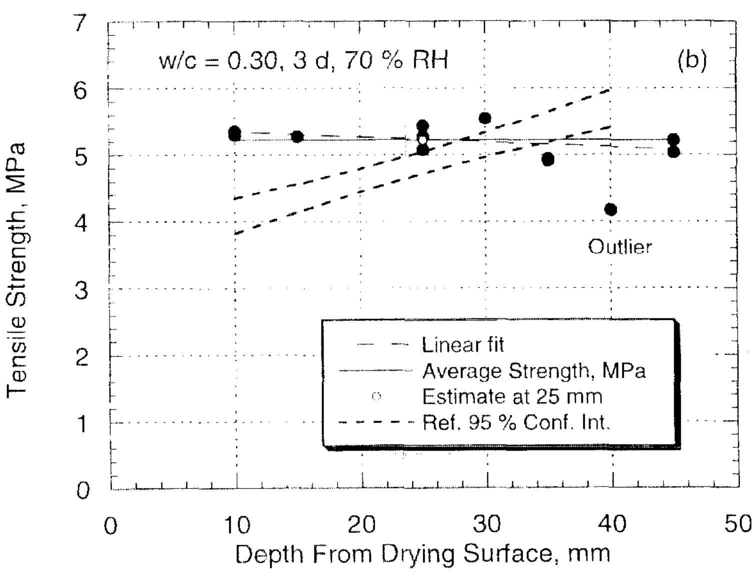


Fig. 9--Tensile strength versus depth for *w/c* = 0.30 with 3 days of moist curing followed by: (a) drying at 50 % RH and (b) drying at 70 % RH

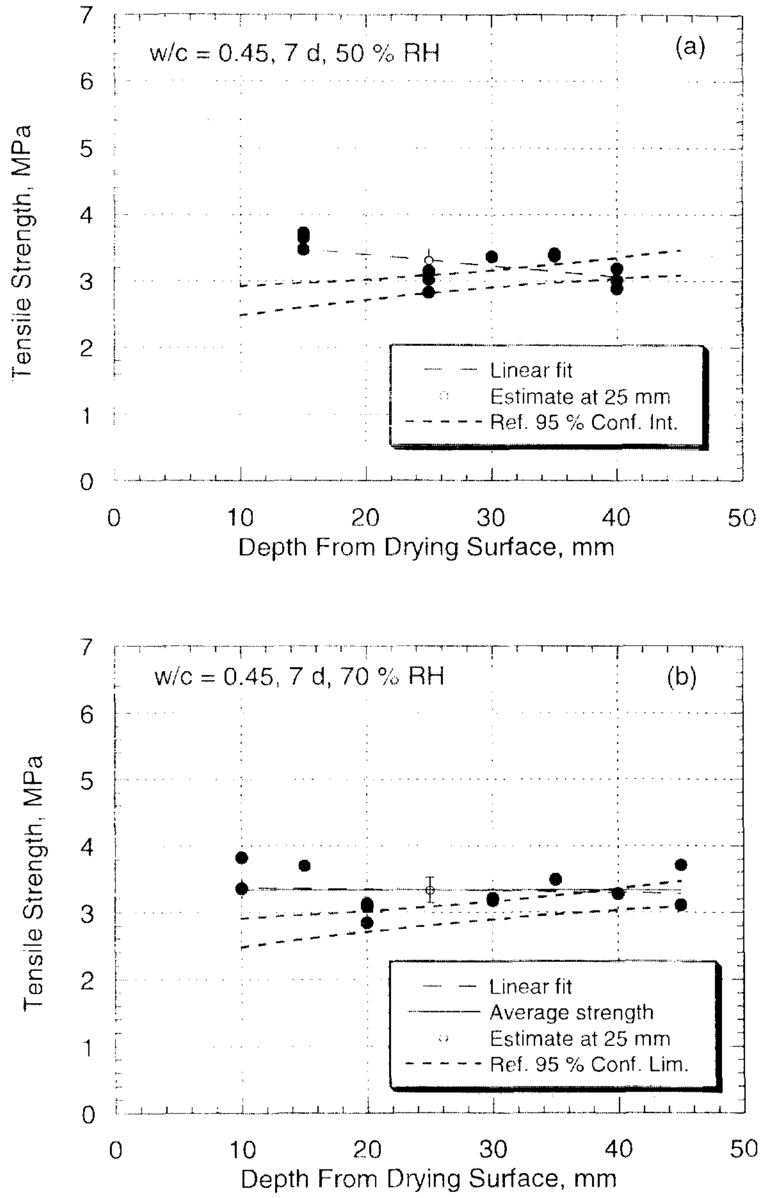


Fig. 12–Tensile strength versus depth for *w/c* = 0.45 with 7 days of moist curing followed by: (a) drying at 50 % RH and (b) drying at 70 % RH

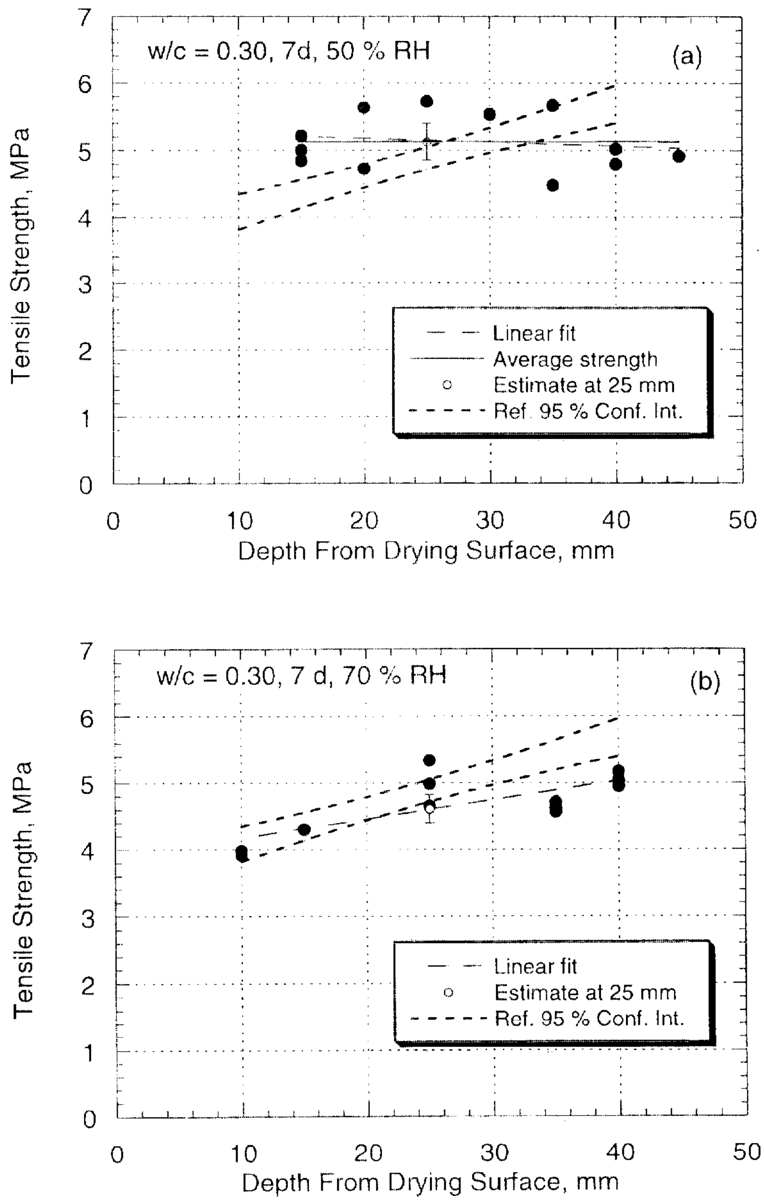


Fig. 11–Tensile strength versus depth for *w/c* = 0.30 with 7 days of moist curing followed by: (a) drying at 50 % RH and (b) drying at 70 % RH

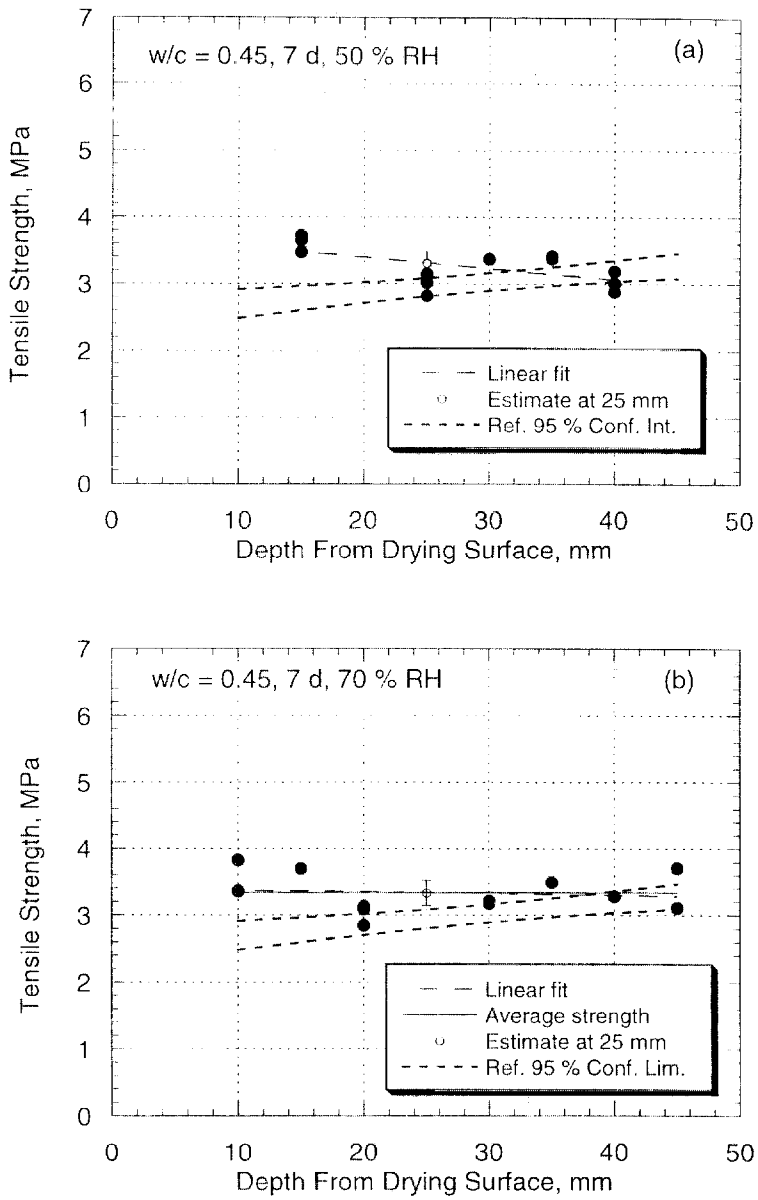


Fig. 12–Tensile strength versus depth for *w/c* = 0.45 with 7 days of moist curing followed by: (a) drying at 50 % RH and (b) drying at 70 % RH

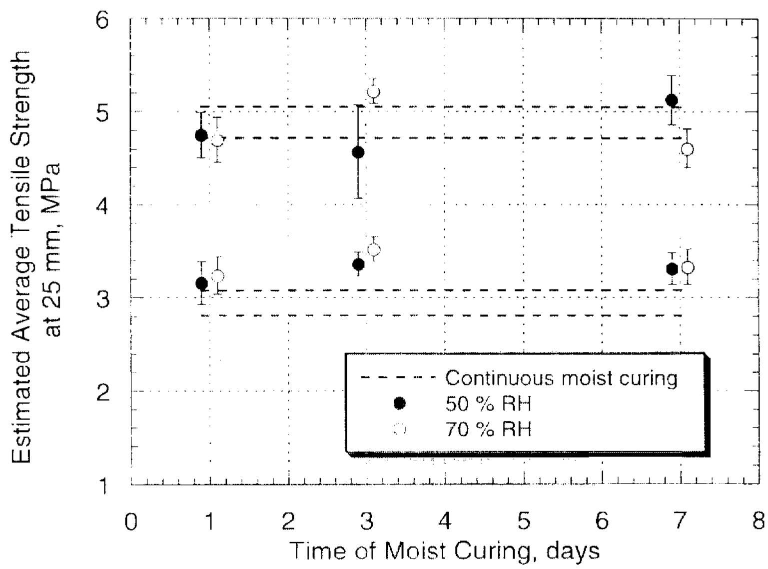


Fig. 13–The 95 % confidence intervals of the estimated average strength at a depth of 25 mm versus the duration of moist curing prior to exposure to drying

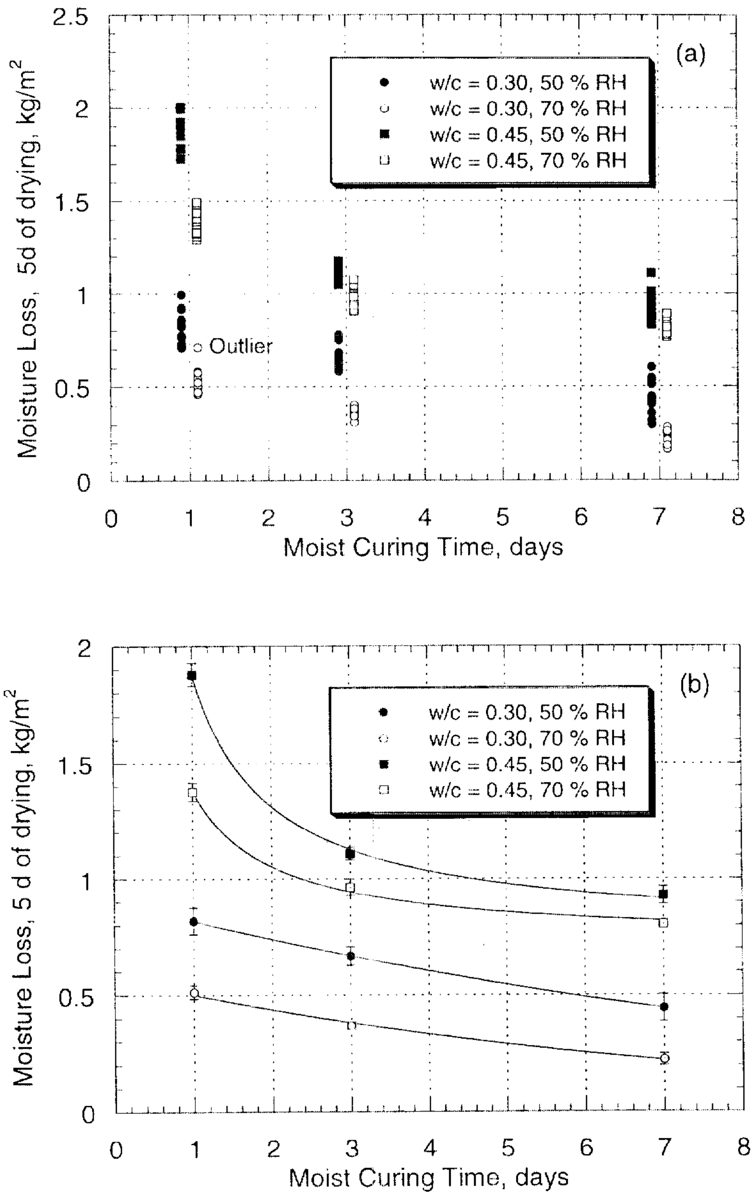


Fig. 14–Moisture loss after 5 days of drying versus the duration of the moist curing period: (a) all data and (b) 95 % confidence intervals of the average mass loss